A Radiofrequency System for the PEGASUS-III Experiment*

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Non-solenoidal Startup Critical Challenge for Spherical Tokamaks

Radiofrequency (RF) injection provides tool for plasma initiation, heating and sustainment on PEGASUS-III

- New RF program enhances startup tools with reactor relevant technology
- May improve local and coaxial helicity injection (LHI and CHI) plasmas
- Readily available 28 GHz source frequency-based approach

Radiofrequency systems can explore:

- Heating in plasma core during helicity injection (HI), reducing resistive losses
- Seeding plasma via pre-ionization
- Handoff for non-inductive ramp up and sustainment following HI startup

PEGASUS-III: Non-solenoidal Startup and Sustainment Experiment

Major Radius	0.48m
Aspect Ratio	1.22
Magnetic Field	≤ 0.6T
Plasma Current	0.3 MA
Densities	< $2x10^{19}$ cm^{-3}
Temperatures	≤ 250 eV

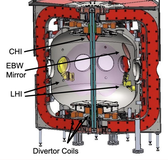
PEGASUS-III Experiment is a spherical tokamak in the Engineering Physics department of UW Madison.

- Lowest aspect ratio ST in the world
- NO central solenoid: Allows for 4x B_T increase

PEGASUS-III Mission: Solve the ST startup plasma challenge by comparing, contrasting and investigating synergistic effects of non-solenoidal current drive techniques using reactor relevant technology

The techniques to be deployed on PEGASUS-III:

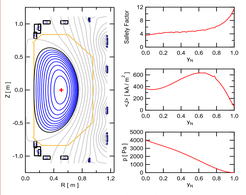
- Local helicity injection (LHI): at high I_p & B_T and longer pulse length
- Coaxial helicity injection (CHI): Transient and sustained
- RF heating and current drive: Electron cyclotron (EC) and electron Bernstein Wave (EBW)



Ray-tracing Calculations Model RF Propagation in PEGASUS-III Scenarios

The 3D ray-tracing code GENRAY[1,2] calculates propagation and absorption of X-mode, O-mode and EBW:

Projected LHI Equilibrium Reconstruction with KFIT



Equilibrium Parameters
Shot 12366, 0.000 ms, Undo 234

I_p	297 kA	R_0	0.434 m
β_t	0.045	a	0.313 m
ℓ_i	0.41	A	1.38
β_p	0.37	κ	2.0
W	9089 J	δ	0.27
B_{T0}	0.339 T	q_{95}	9.19

- RF source frequency = 28 GHz
- Inputs: equilibrium, n_e and T_e profiles
- Analytic expression for OXB mode conversion used in GENRAY:
  - O-X conversion at P_{conv}, $X_e = \frac{\omega_{pe}}{\omega} = 1$, and, for O-mode,
  - $N_{\|opt} = \sqrt{Y_e(P_{conv}) / Y_e(P_{conv})+1}$, $Y_e = \frac{\omega_{ce}}{\omega}$
  - X-B conversion at upper hybrid resonance layer (UHRL), $X_e + Y_e^2 = 1^4$
- GENRAY output coupled to Fokker-Planck code CQL3D[3] to calculate driven current

[1]Smirnov A P, Harvey R W and Kupfer K 1994 A General Ray-Tracing Code (GENRAY) *Bulletin of the American Physical Society* **39** 1626
[2]Smirnov A P and Harvey R W 2003 *The GENRAY Ray Tracing Code* (Del Mar, CA: CompX no. CompX-2000-01)
[3]Harvey R W and McCoy M G 1992 *The CQL3D Fokker-Planck Code* (National Technical Information Service no. DE93002962)
[4]J. Preinhaelter and V. Kopecky,, J. Plasma Physics, 10, part 1, pp.1-12, (1973).

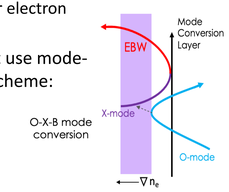
Modeling Results Show Suitability of EBW for Heating on PEGASUS-III

PEGASUS-III plasmas can become overdense, prohibiting ECH

- Plasma becomes overdense, $\omega_{pe} > n\Omega_e$, at 1x10^{19} m^{-3} for 28 GHz source frequency
- However, EBWs propagate in overdense plasmas: electrostatic waves that are absorbed near electron cyclotron harmonics

EBW cannot propagate through vacuum, must use mode-conversion near plasma edge, such as O-X-B scheme:

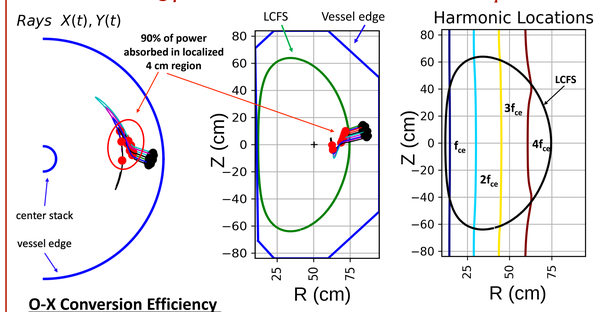
- Requires oblique launch of O-mode
- Optimizing power coupled depends on
  - Local magnetic field
  - Density scale gradient

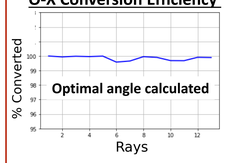


28 GHz source frequency absorbed near EC harmonics:

$$\omega - k_{||}v_{||} - n\Omega = 0$$

Localized Heating ρ ~ 0.4-0.8 with OXB Conversion for $B_T = 0.33$ T

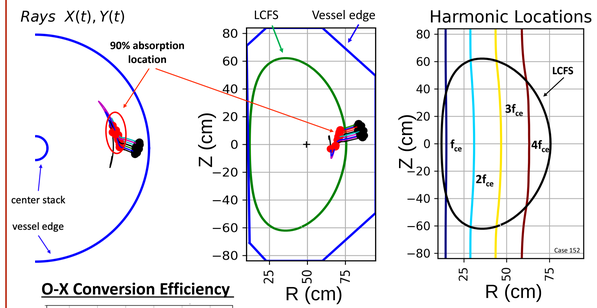


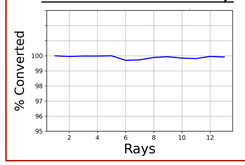


Launcher injects 100 kW power, f_{source} = 28 GHz

- Near midplane launch: $N_{\|}$ range calculated within GENRAY
- 1st run generates optimal launch conditions
- 2nd run incorporates mode conversion, propagation and damping

Localized Heating ρ ~ 0.6-0.8 with OXB Conversion for $B_T = 0.40$ T





Modeling cases demonstrate localized EBW absorption possible at lower end of B_T range for PEGASUS-III

- Absorption improves at higher $B_T(0)$ ~ 0.6 T

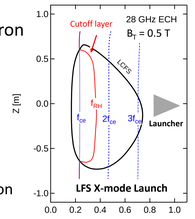
Electron Cyclotron Heating Provides Path to Investigate Helicity Injection Synergies

Density range of helicity-injection plasmas accessible provides scenarios to explore Electron Cyclotron heating (ECH)

- Heating during post-CHI decay phase to significantly increase T_e for NBI sustainment
- T_e heating during LHI for more efficient CD
- Post-LHI heating for subsequent heating, CD

Pure-RF startup scenarios to be investigated

- ECH/ECCD initiation and current channel formation



2nd harmonic EC resonance accessible

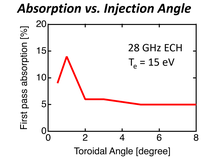
- Significant absorption at 2nd harmonic
- Density cutoff < 5x10^{18} m^{-3} accessible during startup

R [m]

Mode	O1	X1	X2	O2	X3
Frequency	Ω_{ce}	f_{uc}	$2\Omega_{ce}$	$2f_{uc}$	$3\Omega_{ce}$
Density	n_{cr1}	$2n_{cr1}$	$2n_{cr1}$	$4n_{cr1}$	$6n_{cr1}$

ECH Modeling Shows Path to High Absorption During HI

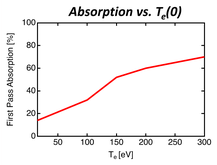
Absorption vs. Injection Angle



Peak 15% first pass absorption estimated for $T_e(0) = 15$ eV

- Results shown for single ray launch
- Launcher at z = 5.5 cm, poloidal angle = 15°, toroidal angle = 1°
- Applicable to CHI targets

Absorption vs. $T_e(0)$

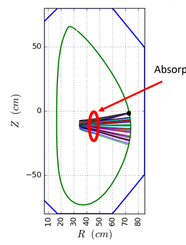


First pass absorption reaches 70% as $T_e(0)$ increases to 300 eV

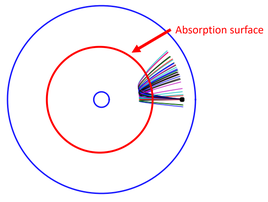
- Existing LHI targets start at T_e = 100 eV, may improve at higher B_T

Virtuous ECH power absorption in core demonstrated for underdense HI plasmas

Poloidal Cross Section

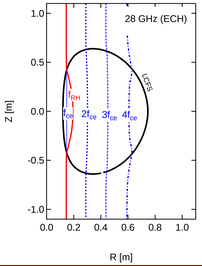


Toroidal Cross Section

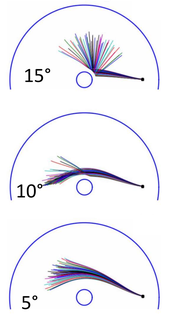


Initial ray tracing for B_T = 0.375 T with toroidal launch angle scan of 5°, 10° and 15°

- First pass absorption is 0% for 3rd, 4th harmonics
- Exploring steerable injection may provide CD



Scan of EC toroidal launch angle



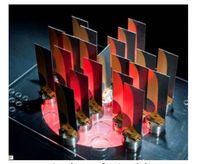
Experimental Equipment of RF System currently under design

Modeling demonstrates 28 GHz suitable for RF injection in PEGASUS-III

- 28 GHz, 200 kW Varian gyrotron with launcher located near midplane on the low field side of vessel
- 80kV-8A power supply being designed and built by PEGASUS-III group

Diagnostics provide tools to investigate RF injection into HI plasmas

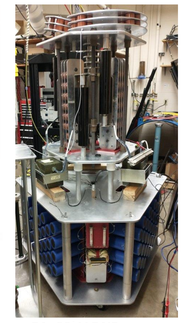
- Synthetic Aperture Microwave Imaging diagnostic (SAMI) on loan from University of York to investigate microwave coupling feasibility
- Soft x-ray camera to study localized EBW current drive
- Sniffer probe to look for evidence of stray radiation during RF injection



Display of Vivaldi antennas used in SAMI

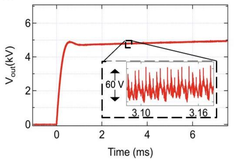


28 GHz Varian Gyrotron



5A, 80kV DNB power supply

5V test confirms power supply produces <1.7% ripple pk-pk



RF Modeling Aids Development of RF System on PEGASUS-III

28 GHz is suitable frequency for RF on PEGASUS-III

- Couples to plasma with high absorption over wide range of B_T
- Central power absorption from EC, EBW achievable in low density and overdense plasmas

Near term goals of program include RF assisted startup:

- Post heating of helicity injection plasmas (EC → EBW)
- Synergistic improvement of LHI plasmas heating to reduce resistive dissipation

Long Term Plans for RF Seek to Enhance Non-Solenoidal Tools on PEGASUS-III

Bold tests of non-solenoidal ST startup using reactor relevant techniques

- Local Helicity Injection
- Coaxial Helicity Injection (transient & sustained)
- RF (EBW, EC) heating
- Future: RF current drive

RF auxiliary heating and CD system will enable long-term scientific campaigns

- Synergistic effects for improving helicity injection CD efficiency
- Plasma handoff/sustainment with RF driven currents
- Pure RF plasma startup

Poster download available from: https://pegasus.ep.wisc.edu